



# Performance Evaluation of Particle Sampling Probes for Emission Measurements of Aircraft Jet Engines

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Prepared under Grant NAG3-2187

National Aeronautics and  
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# **Performance Evaluation of Particle Sampling Probes for Emission Measurements of Aircraft Jet Engines**

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## **Abstract**

Considerable attention has been recently received on the impact of aircraft-produced aerosols upon the global climate. Sampling particles directly from jet engines has been performed by different research groups in US and Europe. However, a large variation has been observed among published data on the conversion efficiency and emission indexes of jet engines. The variation results surely from the differences in test engine types, engine operation conditions, and environmental conditions. The other factor that could result in the observed variation is the performance of sampling probes used. Unfortunately, it is often neglected in the jet engine community. Particle losses during the sampling, transport and dilution processes are often not discussed/considered in literatures. To address this issue, we evaluated the performance of one sampling probe by challenging it with monodisperse particles. A significant performance difference was observed on the sampling probe evaluated under different temperature conditions. Thermophoretic effect, non-isokinetic sampling and turbulence loss contribute to the loss of particles in sampling probes. The results of this study show that particle loss can be dramatic if the sampling probe is not well designed. Further, the result allows ones to recover the actual size distributions emitted from jet engines.

## **Introduction**

It is known that atmospheric aerosols play a key role in the Earth's radiation balance, and thereby strongly influence the global climate. Due to the heavy air travel nowadays, aircraft engines directly emit a great amount of both soot and sulfuric acid particles to the upper troposphere and lower stratosphere. These particles may have negative impact on climate through the processes of inducing the formation of new ice clouds (contrails), modifying physical properties of existing cirrus clouds, and providing additional surface area for heterogeneous chemical reactions such as ozone destruction.

In order to address this issue, researches have been performed to evaluate the emission of jet engines when aircrafts are either on ground or in air. To be able to understand the detail particle formation processes, sampling particles from jet engine exhaust or in the near field has been performed by NASA Subsonic aircraft Contrail and Cloud Effect Special Study (SUCCESS) and SULFUR series experiments by German agency, Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR). For the sulfate particle measurement, the values of  $\xi$ , the conversion efficiency of fuel sulfate to sulfate in the forms of  $\text{SO}_3$  and  $\text{H}_2\text{SO}_4$ , by SUCCESS showed that  $\xi$  does not have a strong dependence with the fuel sulfur content (FSC) (1-3). In contrast, studies of DLR showed a decrease in  $\xi$  with an increase of FSC (4-5). These variations may result from the differences in engine types, engine operation conditions, environmental conditions, and sampling/measuring methods (6). However, a significant difference is found by the comparison of non-volatile particle emission indices (EIs), the amount of pollutant generated per kilogram of fuel burned, measured in NASA B757 exhaust plumes (1, 2)

during the SUCCESS project. Researchers began to suspect that the variation may result from the sampling probe design, sampling losses, and other uncertainties associated with particle size measurement. Unfortunately, the issue had not been addressed in all the related studies. The purpose of this study is focused on the experimental evaluation of the performance of the sampling probe developed by NASA for the accurate measurement of jet engine particle emission.

## Background

In this study, the performance of the sampling probe was evaluated by the comparison of the theoretical and actual dilution ratios. The theoretical ratio is defined by aerosol and dilution flow rates ( $R_f$ ), and the actual ratio is determined by particle concentration measurement ( $R_c$ ). They are defined as:

$$\begin{aligned} R_f &= \text{Outlet } (Q_{\text{out}}) / \text{Inlet flow rate } (Q_{\text{in}}) \\ R_c &= \text{Inlet } (C_{\text{in}}) / \text{Outlet concentration } (C_{\text{out}}) \end{aligned}$$

Ideally, these two should be the same if there is no particle loss.  $R_c$  will increase as the particle loss increases because of the decrease of outlet concentration.  $R_c$  will be greater than  $R_f$  if particle loss was occurred in the sampling probe.

The sampling probe evaluated is designed especially for jet engine exhaust testing. A clean air is provided to cool and dilute the sampled aerosol stream. In addition, a water-cooling jacket is designed to operate the probe under the extreme high temperature condition.

## Experimental Setup

The system setups are shown in Figure 1 and 2. Figure 1 is the setup for evaluating sampling probe at particle size from 50nm to 300 nm. The compressed air was first dry and cleaned by passing through a diffusion dryer and a HEPA filter before it is used in a collision type of atomizer. A flow rate of 2 lpm was controlled by the orifice installed in the atomizer. NaCl solutions were used in the atomizer for this particle size range.

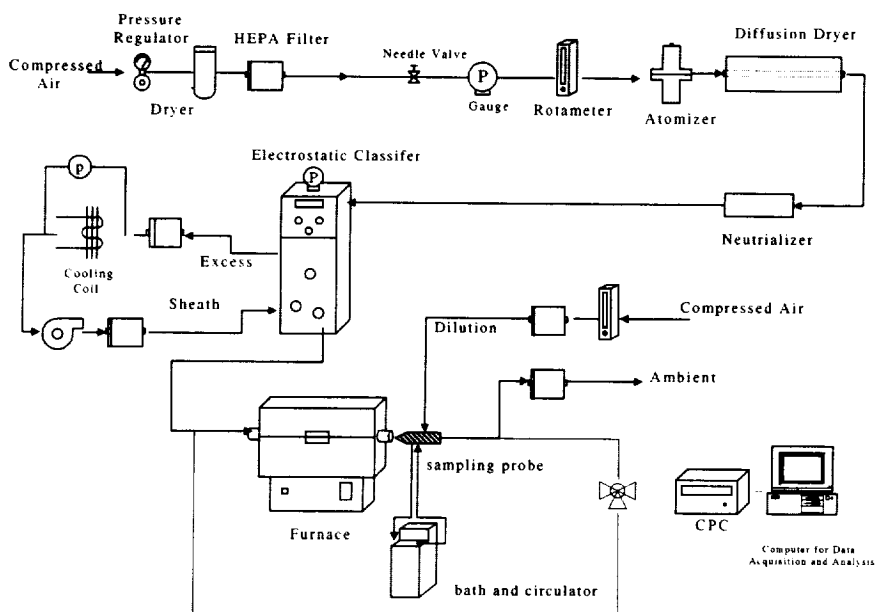


Figure 1. System Setup for 50nm – 300 nm Particles

Two different NaCl solution concentrations, 1% and 0.1% (by weight), were used in order to provide the test particles in the sizes ranging from 50 to 300 nm. Polydisperse NaCl droplets were produced by atomizing NaCl solutions. They were then dried by a diffusion dryer. For getting monodisperse particles, a TSI 3071 electrostatic classifier (Minneapolis, MN) was used. By changing the DMA voltage and sheath flow rate, monodisperse particles of different particle sizes can be selected. In order to improve the control of excess and sheath flows of the classifier, a flow re-circulation loop between excess and sheath air ports was implemented as described in (7). The flow rate in the loop was set to be 5 lpm in order to get particles with the maximum concentration at the particle sizes around 500 nm. A Lindberg/Blue M (Asheville, NC) Module HTF55322A tube furnace with a ceramic tube with OD 5/8" (1.59 cm) and 26" (66.04 cm) in length was used to simulate the high temperature situation of the real applications. In the high temperature testing, the furnace was kept at 300 °C for NaCl particles. The head of test probes was connected to ceramic tubing by Swage lock fitting and placed inside the furnace. The rest of the probe was insulated with a heating tape and insulation material. This arrangement allows the test probe temperature be maintained at 100 °C. It is also the air temperature inside the furnace. A water bath with a circulator was used for cooling. The water temperature was kept at 25 °C throughout the testing. A clean dry air was used as the dilution air. It was varied from zero to 25 lpm. A TSI 3022 condensation particle counter (CPC) was used to measure the particle concentration upstream and downstream of the sampling probes. The actual dilution ratio at different particle sizes is then calculated from the upstream and downstream particle concentration readings.

In order to evaluate sampling probe with particles smaller than 50 nm, we used the evaporation-condensation-classification method to generate monodisperse silver particles. A Nano-DMA was used in this part of experiments. The setup is shown in Figure 2. The temperature of the dilution air for sampling probe was also heated to an elevated temperature by the other Lindberg/Blue Module HTF55322A tube furnace in order to simulate the real operation of the test probe. Both furnaces were heated to 300 and 600 °C for the high temperature simulation. The air temperatures in equilibrium were 105 and 200 °C respectively. Due to the stability of silver particle generation will be affected when we adjusted the three-way valve for upstream and downstream particle concentration measurements, we used two separate CPCs to monitor the upstream and downstream concentration simultaneously instead of one. One CPC is TSI model 3022 and the other is TSI model 3025. Since the operation principles of these two CPCs are different at high particle concentrations. The reading correlation between two CPCs was determined experimentally before we performed this testing. The sampling flow rate of two CPCs was set at 1.5 lpm. This correlation was then used to correct the experimental data collected from two CPCs in order to get actual  $R_c$  values.

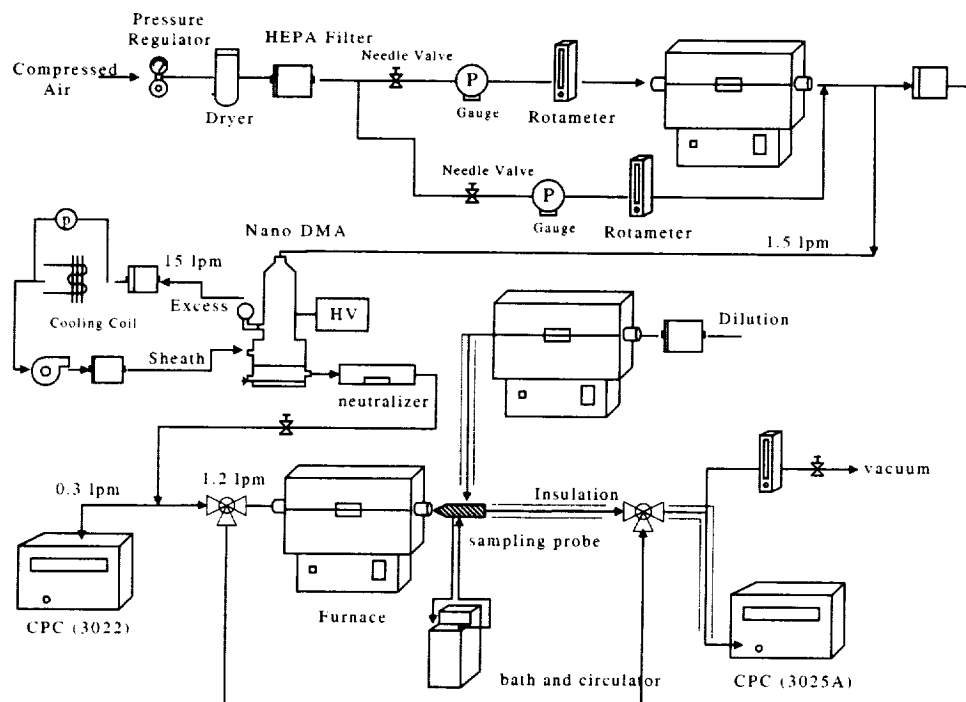


Figure 2. System Setup for 10-50 nm of Particles

## Results and Discussions

### 1. Effect of Particle Sampling Angle

Figure 3 shows the particle penetration through the sampling probe without dilution at different sampling angles, e.g. 0, 45 and 90. The test temperature is 25 °C. The result shows that the probe performance is relatively independent with the sampling angle. Nearly 100% of particles pass through the sampling probe at each tested sampling angle. Although the probe is designed to operate at the super-isokinetic sampling condition, the loss caused by the sampling is negligible. The observation is not surprised. It is because for particles with sizes ranging from 30 to 300 nm they have less particle inertia than those in the supermicron size range. Meanwhile, the particle diffusion loss in this test size range is also negligible because of their less diffusional coefficients than those of particles less than 20 nm, and short aerosol residence time in the test probe.

When the probe was heated to 300 °C, and the cooling water was turned on, the penetration drops to about 80%. It is because of more particle deposition on the inner wall of probe due to the particle thermophoretic effect. Again the particle penetration is independent with the sampling angle as evidenced by the experimental data.

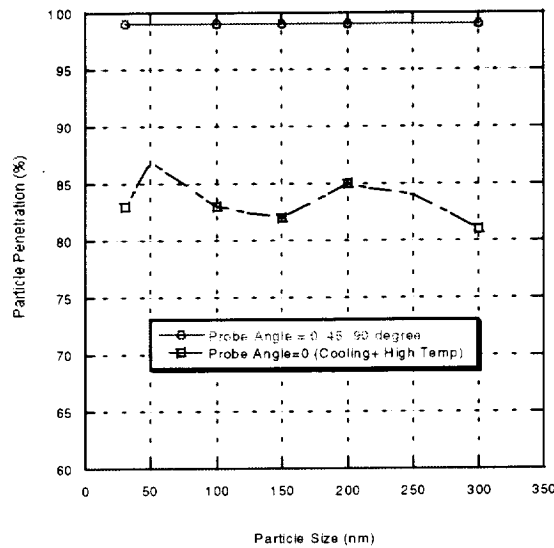
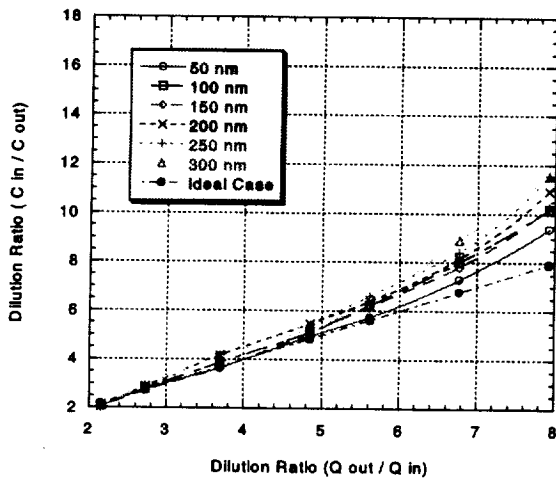


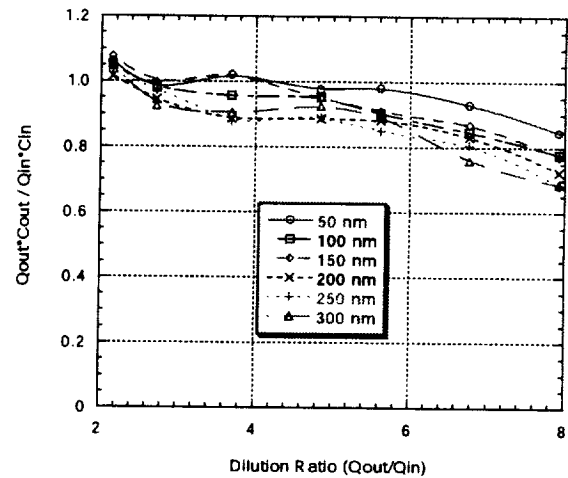
Figure 3 Particle penetrations at Different Test Conditions

## 2. Probe Performance for NaCl Particles of 50 – 300 nm

Figure 4 and Figure 5 show the comparisons of dilution ratios obtained by flow rates and those obtained by CPC reading at room temperature and 300 °C using NaCl particles. It is observed that the loss at both room temperature and 300 °C is increased as the increase of the dilution ratio. Further, the particle loss is also increased as the particle size is increased. This is the typical trend of particle loss when turbulence mixing is occurred. It is also expected that the particle loss at 300 °C is greater than that at room temperature because of the particle thermophoretic effect.

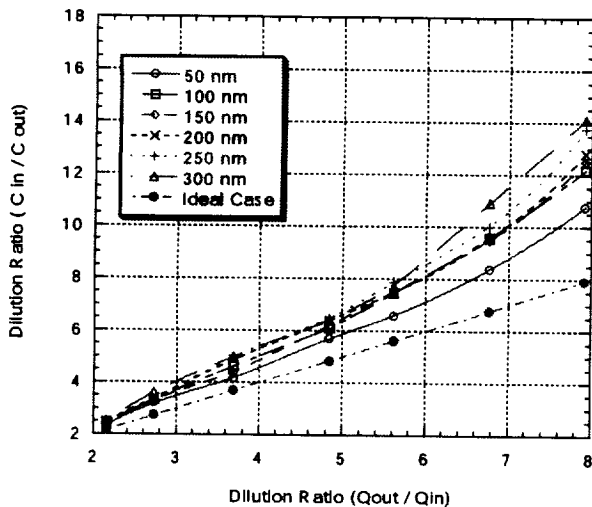


(a)

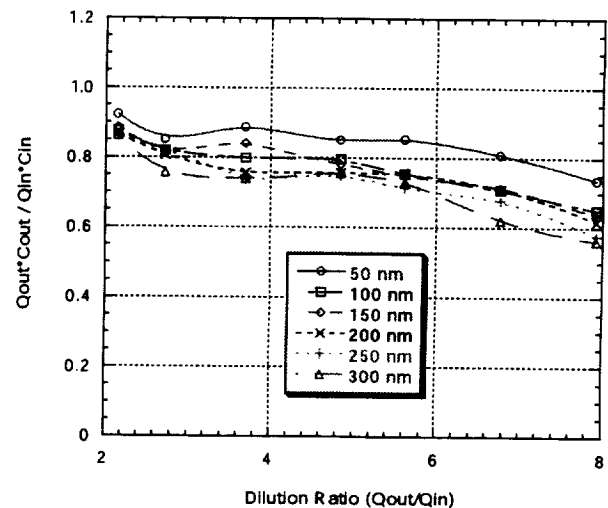


(b)

Figure 4. Dilution Ratio (a) and Penetration Plots (b) at Room Temperature for NaCl particles



(a)



(b)

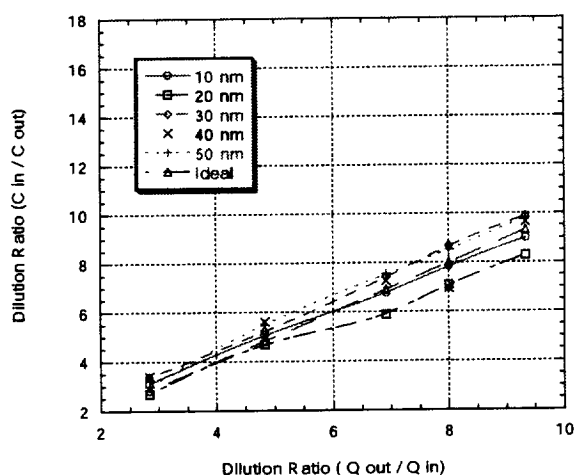
Figure 5. Dilution Ratio (a) and Penetration Plots (b) at 300°C for NaCl Particles

### 3. Probe Performance for Silver Particles of 10-50nm

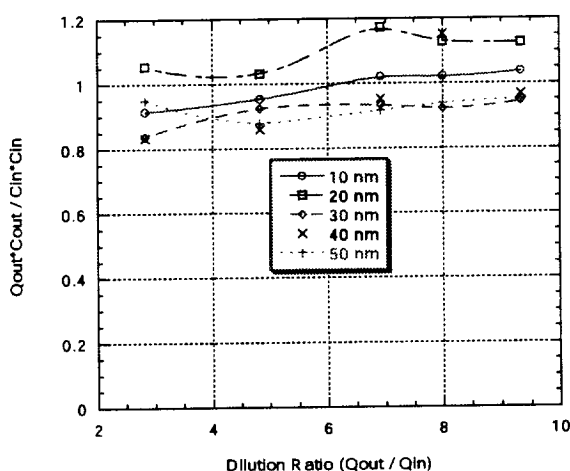
Figure 6 shows the dilution ratio plot at room temperature for silver particles with sizes from 10 to 50 nm. Unlike what observed in Figure 4, there is no significant loss up to the dilution ratio around 9. This shows that for particles smaller than 50nm, the less particle loss will occur due to the dilution process. It is because of the short particle residence time in the sampling probe and negligible particle loss in the turbulent mixing for this size range.



One the other hand, a significant temperature effect on the particle loss has been observed as shown in Figure 7 and 8. In general, the higher temperature results in more particle loss. During the testing, the probe wall temperature was kept at nearly 25 °C and the aerosol steam temperature was kept at the elevated temperature. The temperature difference becomes greater when testing at a higher temperature condition. Under these circumstances, the thermophoretic effect is enhanced and results in more particle loss. Since the effect is weakly dependent on the particle size in this test size range, the slopes of lines are expected to be similar. This is also the trend given by this set of data. Unfortunately, we could not heat the probe to an elevated temperature in order to get the direct proof of this argument. It is because the O-rings used in the probe and test chamber were producing particles and melt when we tried this attempt.



(a)



(b)

Figure 6. Dilution Ratio (a) and Penetration Plots (b) at Room Temperature for Silver Particles

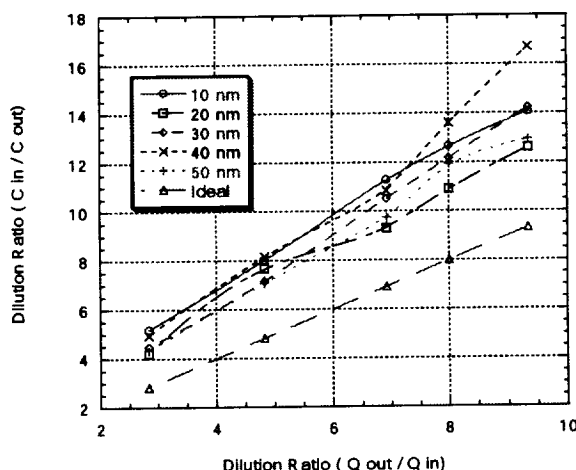
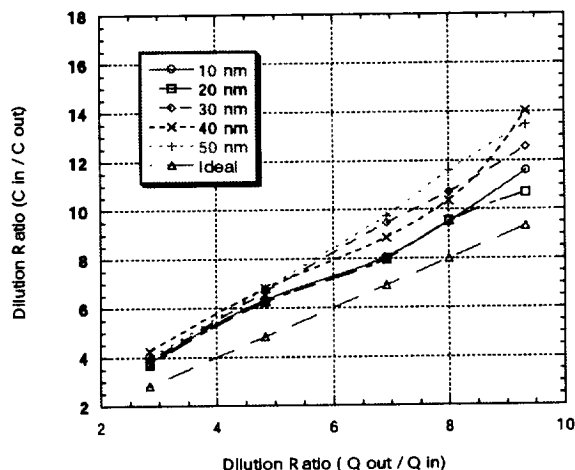


Figure 7a. Dilution Ratio plot at 300°C (Left) and 600 °C (Right) for Silver Particles

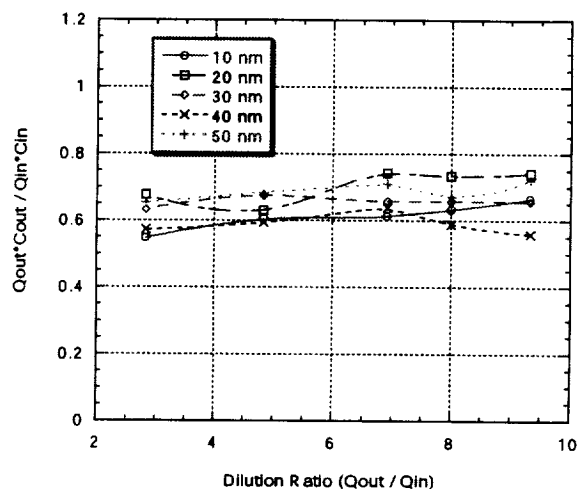
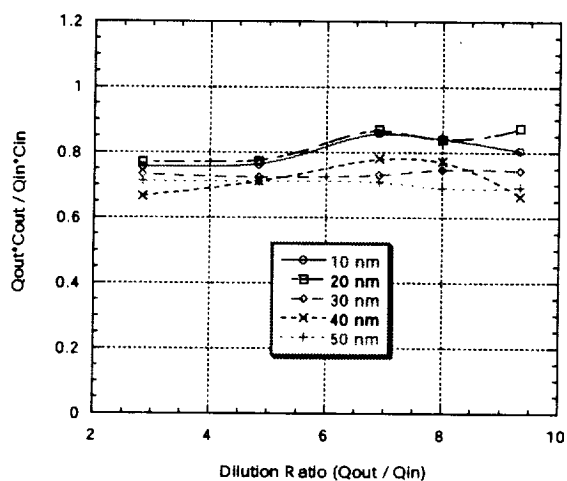


Figure 7b. Penetration Plot at 300°C (Left) and 600 °C (Right) for Silver Particles

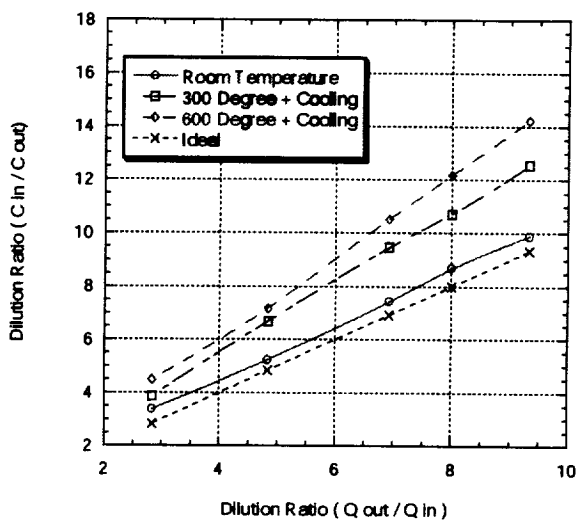
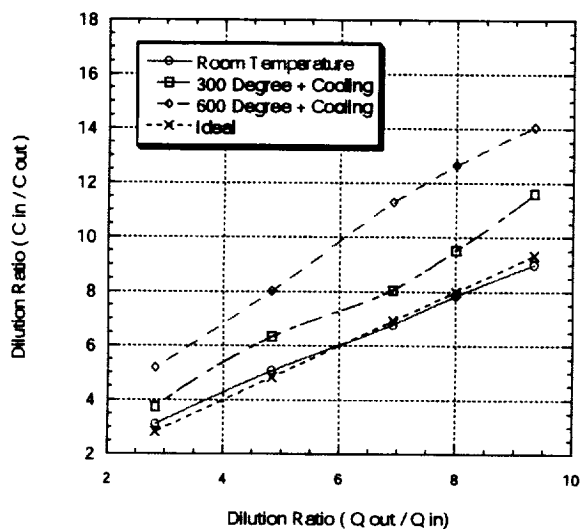


Figure 8a. Dilution Ratio Plot of 10nm (Left) and 30 nm (Right) Silver particles at different test conditions

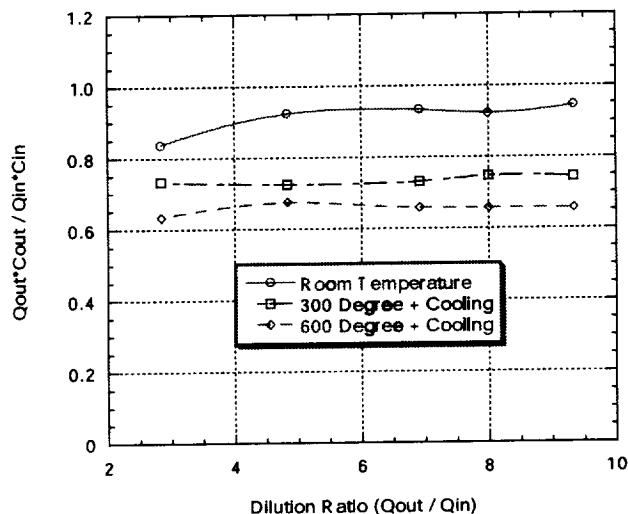
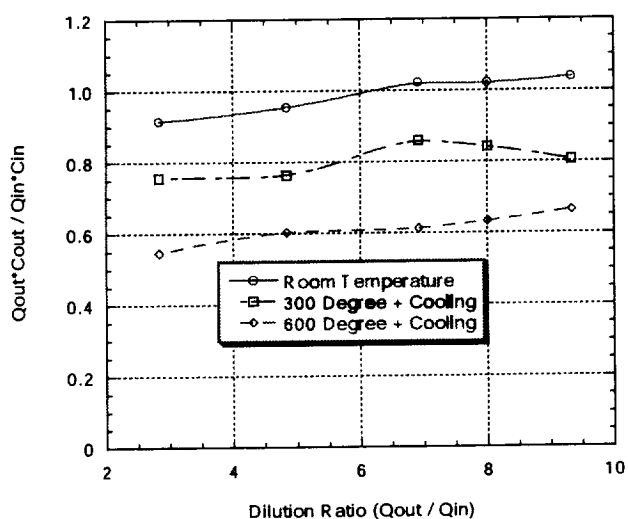


Figure 8b. Penetration Plot of 10nm (Left) and 30 nm (Right) Silver Particles at Different Test Conditions

## Conclusion and Summary

The NASA sampling probe used for jet engine exhaust sampling was tested. Significant performance differences were shown at different operation conditions. Several conclusions can be concluded from this study.

- (1) The sampling angle is not a great concern of this probe for the test size range. It is because of the low particle inertia.
- (2) The particle loss increases with the increase of dilution ratios for particle greater than 50 nm. From the observed trend of particle loss, it is evidenced that the turbulent mixing is happened. It is desirable from the aerosol mixing point of view. It is because the mixing provides a quick response time. On the other hand, the loss of particles can be very significant under the turbulence flow condition especially for larger particles. The balance between these two factors becomes a challenge for the future probe design.
- (3) The high temperature difference between aerosol steam and sampling probe wall is not desired for particle penetration and dilution, especially for nanometer particles. It is because of the thermophoresis effect. From this study, the effect is more pronounced for particles smaller than 50 nm.

Our results show sampling probes do have a great influence on the accuracy of jet engine exhaust sampling. Therefore it is suggested that the probe performance evaluation shall be done before the usage of the probe. The calibration data shall then be used in the data analysis in order to get the actual values of the measurements. The data provided by this report is particularly for this tested NASA probe and shall not be used for other probes.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 2001		3. REPORT TYPE AND DATES COVERED Final Contractor Report
4. TITLE AND SUBTITLE  Performance Evaluation of Particle Sampling Probes for Emission Measurements of Aircraft Jet Engines			5. FUNDING NUMBERS  WU-714-01-20-00 NAG3-2187	
6. AUTHOR(S)  Poshin Lee and Da-Ren Chen				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Minnesota Particle Technology Laboratory Mechanical Engineering Department 100 Church Street, S.E. Minneapolis, Minnesota 55455-0110			8. PERFORMING ORGANIZATION REPORT NUMBER  E-13047	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER  NASA CR-2001-211201	
11. SUPPLEMENTARY NOTES  Project Manager, Terry Sanders, Turbomachinery and Propulsion Systems Division, NASA Glenn Research Center, organization code 5830, 216-433-5849.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified - Unlimited Subject Categories: 07 and 45 Available electronically at <a href="http://gltrs.grc.nasa.gov/GLTRS">http://gltrs.grc.nasa.gov/GLTRS</a> This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  Considerable attention has been recently received on the impact of aircraft-produced aerosols upon the global climate. Sampling particles directly from jet engines has been performed by different research groups in the U.S. and Europe. However, a large variation has been observed among published data on the conversion efficiency and emission indexes of jet engines. The variation results surely from the differences in test engine types, engine operation conditions, and environmental conditions. The other factor that could result in the observed variation is the performance of sampling probes used. Unfortunately, it is often neglected in the jet engine community. Particle losses during the sampling, transport, and dilution processes are often not discussed/considered in literatures. To address this issue, we evaluated the performance of one sampling probe by challenging it with monodisperse particles. A significant performance difference was observed on the sampling probe evaluated under different temperature conditions. Thermophoretic effect, nonisokinetic sampling and turbulence loss contribute to the loss of particles in sampling probes. The results of this study show that particle loss can be dramatic if the sampling probe is not well designed. Further, the result allows ones to recover the actual size distributions emitted from jet engines.				
14. SUBJECT TERMS  Aircraft exhaust; Particle emission; Sampling probe; Jet engine			15. NUMBER OF PAGES 16	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	



